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## Recovery of gait after quadriceps muscle fatigue



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### ABSTRACT

The aim of this study was to investigate the effect of recovery time after quadriceps muscle fatigue on gait in young adults. Forty young adults (20–40 years old) performed three 8-m gait trials at preferred velocity before and after muscle fatigue, and after 5, 10 and 20 min of passive rest. In addition, at each time point, two maximal isometric voluntary contractions were performed. Muscle fatigue was induced by repeated sit-to-stand transfers until task failure. Spatio-temporal, kinetic and muscle activity parameters, measured in the central stride of each trial, were analyzed. Data were compared between before and after the muscle fatigue protocol and after the recovery periods by one-way repeated measures ANOVA. The voluntary force was decreased after the fatigue protocol ( $p < 0.001$ ) and after 5, 10 and 20 min of recovery compared to before the fatigue protocol. Step width ( $p < 0.001$ ) and RMS of biceps femoris ( $p < 0.05$ ) were increased immediately after the fatigue protocol and remained increased after the recovery periods. In addition, stride duration was decreased immediately after the fatigue protocol compared to before and to after 10 and 20 min of rest ( $p < 0.001$ ). The anterior–posterior propulsive impulse was also decreased after the fatigue protocol ( $p < 0.001$ ) and remained low after 5, 10 and 20 min of rest. We conclude that 20 min is not enough to see full recovery of gait after exhaustive quadriceps muscle fatigue.

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## 1. Introduction

Muscle fatigue has been defined as a loss of contractile capacity of the muscle as a consequence of muscle activity, reflected in failure to maintain a required or expected force, in failure to continue working at a given exercise intensity, or in a loss of performance during repeated or continuous activation [1]. Muscle fatigue negatively affects aspects related to balance, such as muscle contractile capacity, coordination and proprioception [2,3]. Consequently, quadriceps muscle fatigue affects gait of young adults irrespective of their physical activity level [4] and type of gait, such as obstacle crossing and stepping down a step [4–7]. It coincides with adjustments in the spatio-temporal

[3,4,6,8,9], kinetic [4,7] and muscle activity [5,8] parameters of gait. Young adults were shown to reduce activity of the quadriceps muscle during gait after exhaustive exercise [5,8,10], which may impair weight acceptance [4] since the quadriceps muscle dissipates most of the energy at contact of the foot with the ground [7,11]. In addition, muscle fatigue coincides with compensatory gait adjustments that enhance gait stability, such as an increased step width and decreased step duration [4,6].

After prolonged exercise and especially after eccentric contractions fatigue and potentially muscle damage may have long-lasting effects [12,13]. Considering the negative effects of muscle fatigue on gait, it is important to know the recovery of spatio-temporal, kinetics and electromyographic parameters and to determine how much time is needed for full recovery. Previous studies indicated negative effects of fatigue after exhaustive exercise on the force generating capacity of muscle [14] and balance [15,16] are negatively affected by muscle fatigue and need 10–20 min to recover after exhaustive muscle fatigue. However, the time needed for recovery of gait parameters after muscle fatigue has to our knowledge not been studied. The period of rest

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required to recover gait parameters after muscle fatigue is important, since around 23–30% of falls in occupational setting occur because of fatigue [17]. Fatigue in these incidents may refer to other processes in addition to muscle fatigue, e.g. mental fatigue. Nevertheless, this study focuses on effects of muscle fatigue only.

The aim of this study was to investigate the effect of different recovery periods (5, 10 and 20 min) after fatiguing quadriceps muscle exercise on gait in young adults. We hypothesized that muscle fatigue would negatively affect gait, which would be reflected in compensatory adjustments to improve stability (i.e. greater step width, decreased step duration). Moreover, we hypothesized that gait changes would return towards baseline values over 20 min of rest.

## 2. Method

Forty individuals aged between 20 and 40 years (age:  $28.9 \pm 5.0$  years; body weight:  $78.6 \pm 14.0$  kg; body height:  $1.76 \pm 0.06$  m; body mass index:  $24.8 \pm 4.0$  kg/m<sup>2</sup>) participated in this study. The exclusion criteria of the study were factors that could interfere with gait and other experimental procedures, such as medication use, presence of osteomyoarticular, neuromuscular or cardio-respiratory diseases and balance and vision disorders. During the sample selection process, 26 initially recruited individuals did not fit the criteria of the study. The study was approved by the local Ethics Committee (# 2055/2008).

Participants were instructed not to perform any strenuous physical activity 48 h before evaluation. The participants performed a warm-up period of 5 min, with walking and stretching. After this period, the participants performed a series of familiarization trials in the leg press instrument (for the maximum voluntary isometric contraction protocol). Subsequently, the participants (Fig. 1):

- 1) filled out a questionnaire on medical history;
- 2) performed the unobstructed gait task;
- 3) performed the maximum voluntary isometric contraction protocol;
- 4) performed the fatigue protocol (sit-to-stand task);
- 5) repeated the second and third items after the fatigue protocol and after 5, 10 and 20 min of rest. The periods of rest were passive with the participants seated.

The participants walked over an 8 m pathway at self-selected speed. Each participant performed three trials before the fatigue protocol, after the fatigue protocol and after 5, 10 and 20 min of rest. We analyzed the stride in the middle of the pathway on the force plates (AccuGait, Advanced Mechanical Technologies, Boston, MA) – 50 cm × 50 cm – with rate of 200 samples/s. Kinetic data were filtered with a 4th order filter with a cutoff frequency of 16 Hz and the magnitude of the ground reaction force was normalized by body weight. Kinematic data were collected by a three-dimensional optoelectronic system (OPTOTRAK Certus), positioned orthogonal to

the plane of progression to the right of the walkway, using a sample rate of 100 samples/s. Four infrared emitters were placed over the following anatomical points: lateral face of calcaneus and head of the fifth metatarsus of the right limb, and medial face of calcaneus and head of the first metatarsus of the left limb. These data were filtered with a 5th order low-pass filter with cutoff frequency of 6 Hz. Muscle activity was assessed using disposable Ag/AgCl surface-electrodes (lead-off area 1.0 cm<sup>2</sup>, inter-electrode distance 2.0 cm) in combination with a signal amplifier (EMG System do Brasil Ltda.). After abrasion and cleaning with alcohol, electrodes were attached over the vastus lateralis and biceps femoris in the right limb. Electrodes and EMG data collection followed the SENIAM guidelines [18]. EMG signals were amplified (1000 times, common mode rejection ratio > 120 dB) and stored on disc (12 bits AD converted, resolution  $\pm 5$  V, sample rate 1000 samples/s). Off-line, EMG signals were band-pass filtered between 20 and 500 Hz and rectified and low-pass filtered at 15 Hz. In addition, values were normalized to peak values of the corresponding signals in the unfatigued trials of each participant. The data acquisition systems were electronically synchronized.

The stride length, stride duration, stride velocity, step width, double support time, braking and propulsive anterior–posterior impulses and root mean square (over a stride—between two consecutive left heel contacts) of vastus lateralis and biceps femoris EMG were analyzed before and after the muscle fatigue protocol and after 5, 10 and 20 min of passive rest in each trial.

Maximum voluntary isometric contractions were performed in a custom-built leg press device [4,6] (Fig. 2). As our fatigue protocol causes fatigue in the whole leg and does not isolate a specific muscle group, we chose the leg press device to test for changes the maximal force produced with the whole leg and not by an isolated muscle group. A load cell with precision of 0.98 N was used in combination with a signal amplifier (EMG System do Brasil Ltda.). The participants were seated in a backward inclined chair, with the hip joint at 90° (180° is full extension) and knee joint at 110° (180° is full extension). Total contraction duration was 5 s. The participant performed the test with both legs, with the instruction to generate as much force as fast as possible. Two attempts were made with 2 min rest between attempts before the fatigue protocol, after the fatigue protocol and after 5, 10 and 20 min of rest. The maximum force generating and median frequency of the power spectrum value of the EMG of the vastus lateralis and biceps femoris in each period were determined. Results of the two attempts at each time point (before and after fatigue, after 5, 10 and 20 min rest) were averaged.

The fatigue protocol was a repeated sit-to-stand task from a chair with arms across the chest [4,5]. The subject performed this task until the participant was unable to continue or when the movement frequency fell below and remained below 0.5 Hz after encouragement and the duration of the protocol was recorded. Rating of perceived exertion was measured by the Borg Scale [19] at the beginning and the end of the fatigue protocol, and after 5, 10 and 20 min of rest.

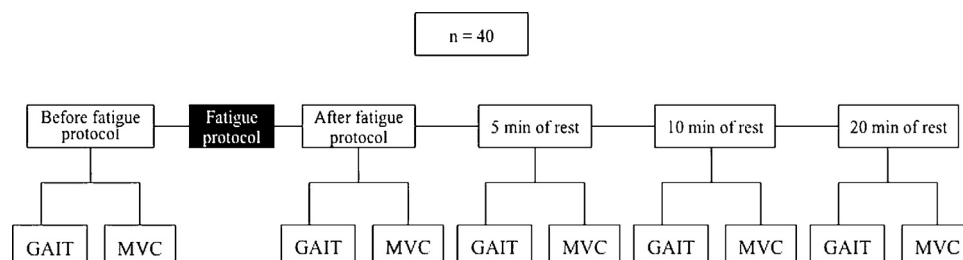
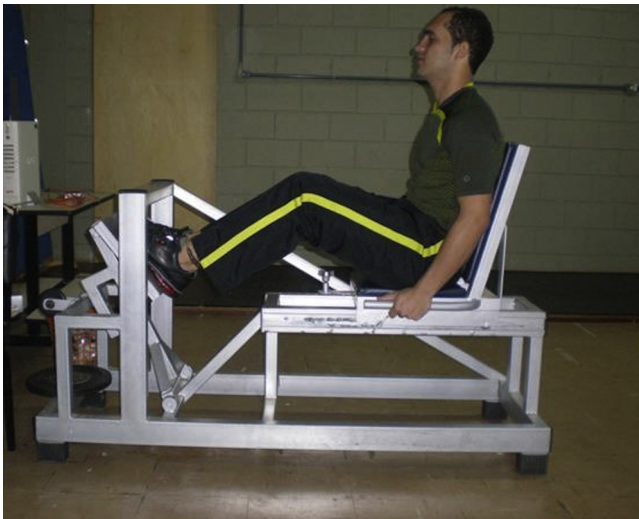


Fig. 1. Experimental design performed by each participant. GAIT, Unobstructed gait task; MVC, maximum voluntary isometric contraction protocol.



**Fig. 2.** Picture of the equipment (custom-built leg press device) for maximum voluntary isometric contractions during knee extension.

### 2.1. Data analysis

The spatiotemporal, kinetic and muscle activity parameters were calculated in Matlab (Version2012—Math Works, Inc.). The dependent variables of interest were statistically analyzed with SPSS 18.0 for Windows. The data were normally distributed, as verified by the Shapiro–Wilk test. The dependent variables were compared using repeated measures ANOVAs, with period (before fatigue  $\times$  after fatigue  $\times$  5 min of rest  $\times$  10 min of rest  $\times$  20 min of rest) as main factor ( $\alpha < 0.05$ ). Polynomial contrast tests were used to localize the differences among periods (Bonferroni adjustments to  $\alpha < 0.005$ ).

### 3. Results

The mean duration of the fatigue protocol was 12.43 min (SD:  $\pm 10.63$  min). The means and standard deviations of the rating of

perceived exertion, maximal isometric voluntary contraction, spatiotemporal, kinetic and electromyography parameters before and after muscle fatigue and after 5, 10 and 20 min of rest are presented in Table 1. ANOVA indicated that the individuals had a higher rating of perceived exertion after muscle fatigue and after the periods of rest (5, 10 and 20 min) than before muscle fatigue ( $p < 0.001$ ). In addition, the rating of perceived exertion immediately after muscle fatigue was higher than after 5, 10 and 20 min of rest ( $p < 0.001$ ) (Table 1). Also force generating capacity was decreased after muscle fatigue and remained decreased after the rest periods ( $p < 0.001$ ). With regard to the EMG signals, vastus lateralis showed a decreased median frequency after the fatigue protocol ( $p < 0.01$ ), which was recovered after 20 min of rest (no differences between before muscle fatigue and 20 min of rest). Median frequency of biceps femoris showed a reduction only directly after the fatigue protocol compared to before ( $p < 0.05$ ), without differences between before the fatigue protocol and after 5, 10 and 20 min of rest.

After the fatigue protocol, participants showed increased step width ( $p < 0.001$ ) and muscle activity of the biceps femoris ( $p < 0.005$ ) and decreased stride duration ( $p < 0.005$ ) and propulsive anterior–posterior impulse ( $p < 0.001$ ) (Table 1). Twenty minutes of rest were not enough for recovery of these gait parameters. Step width ( $p < 0.001$ ), activity of the biceps femoris ( $p < 0.005$ ) and propulsive anterior–posterior impulse ( $p < 0.001$ ) had not returned to baseline values after 20 min of rest. Only stride duration showed clear recovery (after 5 min of rest). None of the other parameters analyzed did show effects of quadriceps muscle fatigue or rest.

### 4. Discussion

The aim of this study was to investigate the effect of different recovery periods (5, 10 and 20 min) after quadriceps muscle fatigue on gait in young adults. As we expected, muscle fatigue coincided with changes in some gait parameters. After the fatigue protocol step width was increased and stride duration decreased. In addition, gait propulsion (decreased propulsive anterior–posterior impulse) and biceps femoris activity (increased RMS of the EMG) were modified after the fatigue protocol. No changes were observed in stride length, stride velocity, double support

**Table 1**

Means and standard deviations of the rating of perceived exertion, maximal isometric voluntary contraction, spatiotemporal, kinetics and electromyography parameters before and after muscle fatigue and after 5, 10 and 20 min of rest.

	Before fatigue	After fatigue	5 min of rest	10 min of rest	20 min of rest
Rate of perceived exertion					
Borg scale	7.10 $\pm$ 1.39*	18.93 $\pm$ 1.28 <sup>§</sup>	8.95 $\pm$ 2.66	9.03 $\pm$ 2.81	8.73 $\pm$ 2.84
Maximal isometric voluntary contraction					
Muscle force (kg/f)	375.65 $\pm$ 13.23*	318.34 $\pm$ 25.90	330.79 $\pm$ 12.02	326.62 $\pm$ 14.76	333.25 $\pm$ 46.11
Median frequency of vastus lateralis	128.84 $\pm$ 37.52*	111.78 $\pm$ 40.30	110.81 $\pm$ 38.46	112.52 $\pm$ 40.02	118.18 $\pm$ 39.71
Median frequency of biceps femoris	103.06 $\pm$ 35.66 <sup>#</sup>	87.94 $\pm$ 28.27	91.89 $\pm$ 19.92	93.64 $\pm$ 26.03	95.33 $\pm$ 25.13
Spatial-temporal parameters					
Stride length (cm)	134.96 $\pm$ 10.85	135.38 $\pm$ 11.98	134.72 $\pm$ 10.93	135.45 $\pm$ 11.83	135.60 $\pm$ 11.74
Step width (cm)	11.45 $\pm$ 2.31*	12.76 $\pm$ 2.66	12.18 $\pm$ 2.38	12.33 $\pm$ 2.72	12.82 $\pm$ 2.78
Stride duration (s)	1.07 $\pm$ 0.08 <sup>#</sup>	1.05 $\pm$ 0.08	1.06 $\pm$ 0.07	1.07 $\pm$ 0.09	1.07 $\pm$ 0.09
Stride velocity (cm/s)	127.31 $\pm$ 15.16	129.39 $\pm$ 15.29	128.15 $\pm$ 14.05	127.99 $\pm$ 18.63	127.83 $\pm$ 17.97
Double support duration (%)	26.79 $\pm$ 2.99	26.69 $\pm$ 3.29	27.84 $\pm$ 3.93	26.43 $\pm$ 2.93	26.43 $\pm$ 2.84
Kinetics parameters					
Braking anterior–posterior impulse (BW)	−0.04 $\pm$ 0.04	−0.05 $\pm$ 0.04	−0.05 $\pm$ 0.04	−0.05 $\pm$ 0.04	−0.05 $\pm$ 0.04
Propulsive anterior–posterior impulse (BW)	0.04 $\pm$ 0.02*	0.03 $\pm$ 0.01	0.03 $\pm$ 0.01	0.03 $\pm$ 0.01	0.03 $\pm$ 0.01
Muscle activity					
RMS vastus lateralis (%)	23.06 $\pm$ 5.09	24.89 $\pm$ 13.18	24.61 $\pm$ 14.01	23.38 $\pm$ 15.55	21.8 $\pm$ 9.89
RMS biceps femoris (%)	21.13 $\pm$ 5.63*	23.63 $\pm$ 9.77	24.89 $\pm$ 12.25	24.12 $\pm$ 11.21	25.01 $\pm$ 11.67

\* Before fatigue is significantly different from other periods.

<sup>#</sup> Before fatigue is significantly different from after fatigue.

<sup>§</sup> After fatigue is significantly different from after 5, 10 and 20 min of rest.

\* Before fatigue is significantly different from after 5 and 10 min of rest.



time, braking impulse and quadriceps muscle activity. Unexpectedly, force generating capacity, step width, propulsive anterior–posterior impulse and muscle activity of the biceps femoris were not recovered after 20 min of rest, in contrast with our second hypothesis. Therefore, in the following paragraphs, we will discuss the apparent absence of recovery of the effects of muscle fatigue on gait parameters after 20 min of rest and offer interpretations of the consequences of such sustained effects on gait.

Several possibly interrelated considerations are to be made regarding the effects of our fatigue protocol. First, in general, gait appears to be quite resistant against fatigue [2,4–7]. The fact that gait is a very sub-maximal task may explain that some gait parameters are not affected by muscle fatigue. Specifically changes in quadriceps muscle activity during gait were, however, expected. Previously, a decrease in the quadriceps activity during a step of the ipsilateral leg was found with muscle fatigue during the approach of a step down [5]. In addition, and in line with although not necessarily coinciding with decreased quadriceps activity, a decrease in knee moments with fatigue was found during the stance phase of the leg first landing on the lower level in stepping down [7]. Also in the approach of a step down and in contrast with the present findings, biceps femoris activity was decreased with fatigue [5]. All in all, these data suggest that muscle fatigue effects cannot be generalized across these different gait types. The increased biceps femoris activity and decreased force generating capacity of the quadriceps muscles found in the present study might affect in particular stance phase kinematics of the knee, where a knee extensor moment is used to generate body weight support. However, increased ankle and hip extensor moments, to which the increased biceps femoris activity might contribute, can potentially compensate for this [20].

Second, the MVC data showed no evidence of neuromuscular recovery. The duration of the fatigue protocol was substantial (~13 min) and consequently the fatigue induced may have required longer recovery times than shorter, high-intensity protocols would [21]. Inducing fatigue under dynamic conditions, such as the sit-to-stand task, does not involve maximum force generating during the exercise. The longer recovery times after contractions of lower force are reportedly due to greater involvement of peripheral factors than in recovery after maximum contractions, where a more central component is suggested [22].

Third, the protocol most likely affected the whole legs and not just the quadriceps muscles. We fatigued participants by a repetitive sit-to-stand task, which we chose for its ecological validity and representativeness of daily life conditions [2]. This fatigue protocol requires high activity of the quadriceps muscles, but involves substantial activity and possibly fatigue of ankle [5] and hip extensors. In addition, the movement to muscle fatigue may also contain eccentric components, which may lead to micro failure and pain [12,13] and might be related to the lack of recovery. Therefore, the fatigue protocol may have affected various muscles of the (whole) leg and not an isolated muscle group. Fatigue of multiple muscles simultaneously requires more time for recovery than fatigue of an isolated muscle [17,23]. Moreover, the neuromuscular system may be able to compensate the deficits caused by muscle fatigue of a single muscle group by adapting activity of antagonistic and synergistic muscles, whereas this may be not possible if these muscle groups, such as we found in our study, are fatigued as well [15,16].

Fourth and final, it has been suggested that with more muscles fatigued there are changes in the supraspinal activity regulating the activity of other muscles, but also of muscle spindles [24]. The effects of fatigue-related changes on proprioception may have contributed to destabilizing the gait. To our knowledge, no data on recovery of proprioception after fatigue is available.

The gait changes observed suggest that walking became more challenging after the muscle fatigue protocol, as reflected in adjustments of gait parameters to deal with the loss of motor control and to maintain stability and safety, corroborating previous studies [3–9]. Specifically, participants increased the base of support and decreased stride duration, probably to deal with reduced balance control in the medio-lateral direction [4–7,25]. In addition, the reduced step frequency implies more time to plan and execute movements and movement adjustments [26]. High force generating capacity of leg muscles is important to perform fast gait adjustments, for example to change direction, avoid an object, or recover from an imbalance. Absence of recovery of force generating capacity after 20 min of rest may thus imply increased risk of falls due to perturbations. We therefore suggest, that to preserve gait stability in the presence of muscle fatigue, subjects choose a more stable gait pattern, to avoid having to make fast gait adjustments and recovery responses. However, the gait changes observed may have a negative effect, in terms of an increased energy cost [27,28], which might prevent recovery or cause further fatigue development during longer walking episodes. Previous studies have suggested that energy cost determines the selection of a certain gait pattern [29], but our results suggest that optimizing energy cost is not the sole objective when walking. The choice for a certain gait pattern may be related to improving gait stability and reducing fall risk rather than minimizing energy cost [30].

Participants increased biceps femoris muscle activity, which is in contrast to our previous study [5]. In addition, propulsive impulses were found to be reduced after the fatigue protocol. The increased biceps femoris activity may have been used to partially compensate a propulsion deficit caused by muscle fatigue or to compensate reduced weight support, through increased hip extension moments [5,31] or through improved knee mechanical efficiency [8,32]. Reduced ability to generate propulsive anterior–posterior impulse diminishes the possibility to increase stride length [30] and, consequently, to improve or correct the balance in the forward direction, which could increase the risk of falling after perturbation such as tripping.

The present study was limited to level gait in healthy young adults. Future studies should investigate the effects of recovery after muscle fatigue in populations that are more affected by fatigue or have an increased fall risk, in different types of gait, such as stepping down a step and obstacle crossing, as well as recovery over a longer time periods after different fatigue protocols. A second limitation was a quite large standard deviation of the endurance time in fatigue protocol. Although levels of fatigue may have differed between participants, maximum force and median frequency of both muscles were decreased after the fatigue protocol in all participants, while the rating of perceived exertion was increased. We therefore believe that this has not strongly affected our results, although it will have limited the statistical power. Finally, we did not analyze the joint kinematics and kinetics (ankle, knee and hip joint angles and moments). In our experimental procedures, we used only four infrared emitters placed over the feet (see Section 2), which prevents the calculation of joint kinematics and kinetics. We recommend for future studies the analysis of these variables to have full gait analysis and to assess the fatigue effects on the different joint levels during walking.

In conclusion, our hypotheses were partially confirmed. Changes in step width and stride duration coincided with muscle fatigue and appear to reflect compensations for impaired gait stability. In addition, propulsive impulses were reduced while biceps femoris activity was increased. Twenty minutes of rest was not enough for recovery of the gait parameters. These findings indicate that the modulations of gait, caused by muscle fatigue, were quite persistent and may be an effect of the persistent decline of force generating capacity of muscle.

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